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DURABILITY OF LOW CEMENT CONTENT CONCRETE

MATERIALS INFORMATION
ENGINEERING MATERIALS OFFICE

Durability of Low Cement Content Concrete

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SUMMARY

The purpose of this study was to gain some knowledge of the durability of concrete mixes with low Portland cement contents. High range water reducers, silica fume, fly ash and slag were used individually, and in some cases in combination, in concrete mixes and specimens were cast for compressive strength and durability testing.

Compressive strengths greater than 30 MPa were reached with substantially less Portland cement than the minimum currently called for in O.P.S.S. 1350⁷. The freeze thaw resistance of all mixes was excellent, however, the salt scaling resistance of most mixes did not meet MTO requirements.

Using materials such as those examined in this report, suppliers have the potential to reduce the Portland cement content of concrete mixes and still meet performance specifications based on compressive strength. Further examination of low Portland cement content concrete needs to be done to ensure adequate concrete durability in the years to come.

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1.0 Introduction

In the past, minimum cement contents have been used to ensure that concrete will have good durability. With the introduction of concrete strength performance specifications, minimum cement contents are generally not specified and the contractor is responsible for the mix design.

The concrete supplier may opt to use high range water reducers (HRWR), also known as superplasticizers, and/or supplementary cementing materials such as silica fume, slag and fly ash to reduce the quantity of Portland cement in the mix while maintaining or increasing compressive strength. The durability of mixes containing low Portland cement contents has not been extensively studied and the main purpose of this project was to gain some knowledge of the durability of such mixes.

Concrete mix design is very complex, especially when new materials are involved and this report is by no means a complete examination of the durability question. Different cements, admixtures, aggregates and a host of other variables could have major impacts on the results obtained. This report merely details the preliminary work done and gives an indication of potential problems.

2.0 Objectives

This evaluation was designed to determine:

- i) if concrete mixes could be designed to meet strength requirements with less Portland cement than currently called for; and
- ii) the potential durability of such mixes.

3.0 Materials

3.1 Cement

The cement used in the work was a blend of Type 10 Portland cements from St. Marys Cement Co., St. Lawrence Cement Co. and Lake Ontario Cement Ltd.. The chemical and physical properties of this

blend complied with the requirements of O.P.S.S. Form 1301¹ and are shown in Tables 1 and 2.

3.2 Aggregates

The fine aggregate was a natural sand of fineness modulus 2.72 and the coarse aggregate was a crushed dolomitic limestone (19 mm nominal maximum size). The coarse aggregate was sieved into four sizes and then recombined to produce the following gradation:

Sieve Size	% Retained
19 mm	0
13.2 mm	33
9.5 mm	66
4.75 mm	100

3.3 Supplementary Cementing Materials

The silica fume was from SKW Canada Inc. of Quebec, slag was from Standard Slag Cement Co. and the fly ash was a class "C" fly ash from Great Lakes Fly Ash (source Detroit Edison, St. Clair, Michigan). Their chemical and physical properties met the requirements of CAN3-A23.5-M-86² and are shown in Tables 1 and 2.

Table 1: Chemical Properties of Cement, Fly Ash, Silica Fume and Slag

IDENTIFICATION	Portland Cement Type 10	CAN3-A5-M83 for Portland Cement Type 10	Fly Ash Type "C"	CAN3-A23.5 M-86 for Fly Ash Type "C"	Silica Fume	CAN3-A23.5 M-86 for Silica Fume	Slag	CAN3-A23.5 M-86 for Slag
Loss on ignition, %	1.31	max. 3.0	0.85	max. 6.0	3.30	max. 6.0	1.06	-
Insoluble residue, %	0.24	max. 1.0	0.42	-	4.30	-	0.41	-
Tricalcium aluminate, %	11.67	-	38.34	-	-	-	30.74	-
Sulphur trioxide, %	3.40	max. 3.5*	3.97	max. 5.0	-	max. 1.0	0.81	max. 5.0
Magnesium oxide, %	3.21	max. 5.0	4.72	-	-	-	14.08	-
Sodium oxide, %	0.27	-	5.05	-	0.07	-	0.27	-
Potassium oxide, %	1.04	-	0.65	-	0.31	-	0.67	-
Alkali content, %	0.95	-	5.48	-	-	-	0.71	-
Silicon dioxide, %	19.81	-	31.90	-	90.50	min. 85	35.53	-
Aluminum oxide, %	6.03	-	17.93	-	0.80	-	11.88	-
Ferric oxide, %	2.55	-	5.43	-	-	-	0.44	-
Calcium oxide, %	62.18	-	25.62	-	-	-	34.94	-
Moisture content, %	-	-	0.23	max. 3.0	0.46	max. 3.0	0.44	max. 3.0

* maximum 3.0 % if the C3A $\leq$ 7.5 %

TABLE 2. PHYSICAL PROPERTIES OF PORTLAND CEMENTS, FLY ASH,
SILICA FUME AND SLAG USED IN THE PROGRAM

IDENTIFICATION	Portland Cement Type 10 Blend	CAN3-A5-M83 for Portland Cement Type 10	Fly Ash Type "C"	CAN3-A23.5 M-86 for Fly Ash Type "C"	Silica Fume	CAN3-A23.5 M-86 for Silica Fume	Slag	CAN3-A23.5 M-86 for Slag
Fineness -pass 45 um sieve, %	86.7	min. 72	84.81	min. 66	98.1	min. 90	81.5	min. 80
-Blaine, m ² /kg	355.9	-	484.8	-	-	-	449.4	-
Soundness, % expansion *	0.214	max. 1	0.544	max. 0.8	0.068	max. 0.2	0.064	max. 0.5
Time of setting, minutes	150	45-360	97	-	180	-	170	-
False set, %	54.3	min. 50	-	-	-	-	-	-
Increase of drying shrinkage of mortar bars, 28 days %	-	-	0.00	max. 0.03	0.022	max. 0.03	-	-
Relative density	-	-	2.7	-	2.13	-	2.88	-
Accelerated pozzolanic activity index, %	-	-	91.6	min. 68	132.7	min. 85	-	-
Pozzolanic activity index, %	-	-	95.4	min. 75	-	-	-	-
Slag activity index, %	-	-	-	-	-	-	100.3	80
Compressive strength, MPa								
3d	25.4	min. 12.5	-	-	-	-	-	-
7d	27.8	min. 18.0	-	-	-	-	-	-
28d	38.6	min. 26.5	-	-	-	-	-	-

* Note: test performed using 10% silica fume

3.4 Admixtures

The superplasticizer used was a naphthalene sulphonate type (Mulcoplast CH from Mulco Inc.). Air entraining admixtures and regular water reducers complied with the requirements of O.P.S.S Form 1303³ and were used as shown in Table 5.

4.0 Test Program

A total of 14 mixes were designed and batched as shown in Table 3.

All of the mixes in this project were designed to have approximately the same strength (36 to 39 MPa) in order to examine the influence of cement content and various additives on durability.

The amount of supplementary cementing materials added to the mix is expressed as a percentage by mass of the type 10 cement. The water/cement ratios stated in the report are actually water/cement + supplementary cementing materials (w/c+s) ratios where appropriate.

Table 3: Test Program

Mix	Laboratory Number	Cement Content (kg)	Water Reducer (Y/-)*	HRWR (Y/-)*	Silica Fume (%)	Fly Ash (%)	Slag (%)
Controls							
Cont-1	L880/87	320	Y	-	-	-	-
HRWR							
HR-2B	L723/88	270	-	Y	-	-	-
Silica Fume							
SF-1	L918/87	280	-	Y	5	-	-
SF-2	L754/88	230	-	Y	5	-	-
SF-2B	L903/88	230	-	Y	5	-	-
SF-3	L755/88	210	-	Y	10	-	-
SF-4	L856/88	250	Y	-	5	-	-
Fly Ash							
FA-1	L778/88	270	Y	-	-	10	-
FA-2	L779/88	245	-	Y	-	10	-
FA-2B	L905/88	245	-	Y	-	10	-
FA-3	L792/88	225	-	Y	-	20	-
Combinations							
C-1	L852/88	230	Y	-	-	10	15
C-2	L854/88	190	-	Y	5	10	15
C-3	L906/88	190	-	Y	5	-	25

* Y indicates that it was used

- indicates that it was not used

The following were kept constant for all mixes:

- Slump 80 ± 10 mm
- Air Content 7 ± 1 % (accepted up to 8.5%)
- Cement Type Standard MTO lab blend
- Aggregate Type Standard MTO lab aggregate

A single 50 L batch (45 L for mixes SF-2, SF-2b and SF-3) was made for each mix design. Mixes SF-2B and FA-2B were repeats of SF-2 and FA-2 respectively. Specimens were fabricated and cured as shown in Table 4. The fresh concrete tests were carried out in accordance with the appropriate method of CSA standard CAN3-A23.2-M774.

Table 4: Test Methods

TEST	SPECIMEN		# OF SPECIMENS	CURING REGIME	TEST METHOD
	TYPE	SIZE, mm			
Compressive strength 7,28,90d	cylinder	100x200	4 for each age	Moisture room	CAN3-A23.2-M77 Method A23.2-9C (see reference 4)
Freeze-thaw	prism	75X75x400	3	Moisture room for 28 d	ASTM C 666-84 Procedure A (see reference 5)
Salt scaling	slab	300x30x75	2	Moisture room for 14 d followed by storage for 14 d at normal lab air conditions	ASTM C 672-84 with the exceptions described under the test procedure in this report (see reference 5)
Rapid chloride permeability	disk*	100x50*	1	Moisture room for 28 d	AASHTO designation: T277-83 I (see reference 6)
Air void system					ASTM C 457-82a (see reference 5)

* Cut from a 100x200 mm cylinder

Mix proportions and fresh concrete test results are shown in Table 5.

TABLE 5. MIX PROPORTIONS AND FRESH CONCRETE TEST RESULTS

	CONTROL Cont-1 L880/87	HRWR HR-1 L723/88	SILICA FUME				FLY ASH				COMBINATIONS			
			SF-1 L918/87	SF-2 L754/88	SF-2B L903/88	SF-3 L755/88	SF-4 L856/88	FA-1 L778/88	FA-2 L779/88	FA-2B L905/88	FA-3 L792/88	C-1 L852/88	C-2 L854/88	C-3 L906/88
Cement, kg	16.0	13.5	14.0	10.4	10.4	9.5	12.5	13.5	12.3	12.1	11.3	11.5	9.5	9.5
Pozzolan, kg	-	-	0.7	0.5	0.5	0.9	0.6	1.4	1.2	1.4	2.3	2.9	2.9	2.9
Coarse Aggregate, kg	55.5	53.7	55.5	48.3	48.3	48.3	54.0	53.7	53.7	53.7	52.9	54.0	54.0	54.1
Fine Aggregate, kg	36.0	38.1	36.7	36.2	36.2	36.3	39.8	37.8	43.0	43.0	43.8	38.3	44.6	43.1
Water Reducer, ml	45.6	-	-	-	-	-	32.8	42.5	-	-	-	36.0	-	-
HR Water Reducer, ml	-	122.0	147.0	90.0	90.0	100.0	-	-	122.0	122.0	122.0	-	112.0	112.0
Air entraining agent, ml	4.3	12.0	12.0	9.0	9.0	9.0	9.5	4.7	11.0	9.0	12.0	12.0	12.0	11.0
Total Water, kg	8.23	7.13	7.62	6.55	6.55	6.70	8.10	8.10	7.48	7.00	7.40	7.85	7.45	7.20
Density, kg/m3	2333	2347	2365	2312	2344	2305	2301	2330	2344	2375	2340	2369	2312	2322
Yield, L	49.6	47.9	48.4	44.2	44.0	44.2	50.0	49.2	50.2	49.0	50.3	48.4	51.2	50.0
Cementitious Mat., kg/m3	322.6	281.8	303.7	246.9	247.7	235.4	262.1	303.2	268.7	275.5	270.4	297.8	242.0	248.0
W/C+S Ratio	0.458	0.432	0.450	0.506	0.509	0.545	0.542	0.460	0.459	0.430	0.454	0.476	0.520	0.484
Slump, mm	80	70	75	90	85	85	80	75	90	70	75	85	85	75
Air Content, %	6.5	7.7	6.0	8.0	6.8	8.2	8.3	7.5	7.2	6.5	7.0	8.5	7.9	7.7

Water Reducers

PDA 25XL L880/87, L778/88
TCDA XA L856/88, L852/88

Air Entraining Admixtures

Pro-Air L778/88
Airex "L" L880/87, L918/87
Air "X-Tra" all others

5.0 Test Procedures

The test procedure for each of the tests carried out is shown in Table 4. Where freeze/thaw cycle tests could not begin after 14 d, the specimens were wrapped in plastic bags and stored at $-18 \pm 2^{\circ}\text{C}$ until testing could commence. The length change, weight change and relative dynamic modulus of elasticity were calculated using the original values obtained after removal from the moulds as base values.

The salt scaling test was carried out as described in ASTM C 672-84⁵ with the following modifications:

- 1) Precast dykes were secured with a mortar mix to a matching recess cast along the perimeter of the slab and sealed with an epoxy.
- 2) Where salt scaling tests could not begin after 28 d, the slabs were wrapped in plastic bags and stored at $-18 \pm 2^{\circ}\text{C}$ until testing could commence.
- 3) The deicing agent was a 3% sodium chloride solution.
- 4) The cumulative mass loss was determined after each 5 cycles of freezing and thawing for each slab and averaged for the pairs. The mass loss is the dry mass of the flaked off concrete.

6.0 Discussion of Test Results

A summary of test results is shown in Table 6.

6.1 Compressive Strength

Compressive strengths at 28 d ranged from 29 to 41 MPa, with the exception of mix SF-1, the first silica fume mix attempted, which had considerably higher strength (52 MPa). Although not all the mixes met the strength target of 36 to 39 MPa, the purpose of this study was to gain information and therefore the durability tests were carried out. Variations in the mix design could have adjusted the strengths to meet the target, however it was not considered necessary for this project.

TABLE 6: TEST RESULTS OF HARDENED CONCRETE

Design Mix Proportions	Control Cont-1 L860/87	HFMR HR-1 L723/87	Silica Fume				Fly Ash			Combinations				
			SF-1 L918/87	SF-2 L754/88	SF-2B L903/88	SF-3 L755/88	SF-4 L856/88	FA-1 L778/88	FA-2 L779/88	FA-2B L905/88	FA-3 L792/88	C-1 L852/88	C-2 L854/88	C-3 L906/88
Cement, kg/m ³	320	270	280	230	230	210	250	270	245	242	225	230	190	190
Silica Fume, kg/m ³	-	-	14.0	11.5	11.5	21.0	12.5	-	-	-	-	-	9.5	10.0
Fly Ash, kg/m ³	-	-	-	-	-	-	-	27.0	24.5	26.0	45.0	23.0	19.0	-
Slag, kg/m ³	-	-	-	-	-	-	-	-	-	-	-	34.5	28.5	48
Total cementitious, kg/m ³	320	270	294	241.5	241.5	231	262.5	297	269.5	270	270	287.5	247	248
HFMR	-	yes	yes	yes	yes	yes	-	-	yes	yes	yes	-	yes	yes
Compressive Strength,														
MPa 7 d	29.6	30.5	38.6	25.6	27.4	25.7	23.3	29.1	29.3	31.0	28.1	21.5	24.5	28.4
28 d	37.7	37.0	52.5	39.6	37.8	40.5	31.7	32.2	33.6	36.4	35.2	28.9	36.4	38.2
90 d	45.8	44.0	55.8	40.9	43.3	41.0	35.1	39.3	41.0	46.0	43.7	33.7	40.2	43.2
Freeze Thaw Resistance														
Durability factor, %	96.3	96.0	91.2	94.0	93.2	91.5	92.8	94.4	94.8	95.4	95.9	93.9	96.2	92.8
Mass Loss, %	-0.14	-0.37	+0.03	-0.24	-0.18	-0.07	-0.09	-0.30	-0.17	-0.01	-0.18	-0.18	-0.22	-0.09
Expansion, %	+0.007	+0.012	+0.013	-0.01	+0.008	+0.005	+0.001	+0.011	+0.002	+0.007	+0.026	+0.005	0.014	+0.007
Salt Scaling Resistance														
Mass Loss, kg/m ² at 5 cycles	0.387	0.040	0.036	0.695	0.460	1.530	0.350	0.281	0.355	0.065	0.621	0.339	0.822	1.351
10	0.667	0.076	0.059	1.106	0.916	1.910	0.446	0.450	0.528	0.123	0.912	0.502	0.984	1.823
15	0.723	0.103	0.077	1.202	1.074	2.016	0.496	0.700	0.646	0.203	1.013	0.558	1.047	2.067
20	0.747	0.116	0.093	1.233	1.135	2.063	0.539	0.815	0.732	0.233	1.091	0.578	1.102	2.121
25	0.784	0.123	0.116	1.249	1.198	2.078	0.577	0.927	0.926	0.248	1.183	0.666	1.191	2.160
30	0.814	0.131	0.134	1.262	1.239	2.093	0.622	1.036	0.961	0.259	1.246	0.762	1.346	2.221
35	0.857	0.137	0.225	1.269	1.251	2.103	0.670	1.099	0.984	0.265	1.271	0.847	1.520	2.257
40	0.889	0.141	0.337	1.282	1.260	2.118	0.903	1.147	1.001	0.270	1.303	0.900	1.674	2.280
45	0.904	0.150	0.549	1.286	1.273	2.126	0.955	1.183	1.066	0.278	1.336	0.987	1.863	2.301
50	0.918	0.167	0.732	1.300	1.283	2.136	0.975	1.210	1.095	0.283	1.363	1.081	2.011	2.323
Air Void System														
Air Void Content, %	5.9	5.0	3.7	N.T.	4.5	5.8	N.T.	N.T.	4.8	N.T.	N.T.	N.T.	N.T.	5.2
Specific Surface, mm ² -1	35.1	27.1	18.5	N.T.	26.2	23.7	N.T.	N.T.	20.6	N.T.	N.T.	N.T.	N.T.	24.3
Spacing Factor, mm	0.121	0.171	0.286	N.T.	0.170	0.144	N.T.	N.T.	0.211	N.T.	N.T.	N.T.	N.T.	0.157
Chloride Permeability,														
Coulombs	2616*	3138	702*	1326	1031	789	675	2559	2133	2942*	591	318	562	982

* Average of 2 tests.

N.T. - not tested

Use of a high range water reducer to reduce the water content enabled mix HR-1 to achieve the same strength as the control mix (Cont-1) with 50 kg/m³ less cement.

Silica fume mixes with the addition of a HRWR (SF-1 to SF-3) had equal or greater 28 d strengths than the control with a reduction in total cementitious material of up to 90 kg/m³. Mix SF-4, with no HRWR added, had a 67 kg/m³ reduction. However, there was a corresponding 6 MPa drop in 28 d strength. The strength gain from 28 d to 90 d was low for four of the silica fume mixes ranging from .5 MPa to 3.4 MPa and was 5.4 MPa for mix SF-2B.

Mix FA-1, without HRWR, had a reduction of total cementitious material of 20 kg/m³ but also had a 5 MPa reduction in 28 d strength. Mixes FA-2, 2B and 3, all with HRWR, had approximately the same strength as the control with a 50 kg/m³ reduction. These mixes are similar to HR-1 except that some of the cement was replaced by fly ash.

Combination mixes, C-2 and C-3, had HRWR, and silica fume and showed, similar strengths to the control. They had approximately 70 kg/m³ less cementitious material than the control. Mix C-1 without HRWR showed a reduction in strength corresponding to the reduction in cementitious material.

6.2 Freeze Thaw Resistance

All mixes exhibited good freeze thaw resistance with durability factors greater than 90% at 300 cycles. Mass loss and expansion were low, ranging from -0.37% to +0.03% and +0.026% to -0.01% respectively.

6.3 Salt Scaling Resistance

Concrete mixes which show scaling losses less than 0.8 kg/m² after 50 cycles are generally considered by MTO to be resistant to salt scaling. Most of the mixes examined had scaling losses ranging from 0.9 to 1.4 kg/m³.

HR-1 had a w/c ratio of 0.43 and exhibited very little scaling (0.17 kg/m²).

The silica fume mixes had scaling losses ranging from 0.73 to 2.14 kg/m². SF-3, which had the lowest cementitious content and 10% silica fume added, had scaling losses of 1.5 kg/m² after 5 cycles.

The fly ash mixes, with the exception of FA-2B (0.28 kg/m²), had scaling losses from 1.10 to 1.36 kg/m². Although basically a repeat of FA-2, FA-2B had a lower w/c+s ratio and higher 28 d strength (approximately 5 MPa).

C-2 and C-3 had similar cementitious contents (248 kg/m³) and 28 d strengths and both exhibited substantial scaling (2.01 and 2.32 kg/m² respectively). Although C-1 had a lower 28 d strength than C-2 and C-3 (29 MPa versus 36 and 38 MPa), its cementitious content was 40 kg/m³ higher and the scaling loss was much lower (1.08 kg/m²).

6.4 Air Void System

A substantial loss in air content between the plastic and hardened concrete was seen in 6 of the 7 mixes examined. The loss in air was 2.3 to 2.7% for 6 mixes (all superplasticized) and 0.6% for the control mix (no superplasticizer).

Some later mixes were accepted with high air contents (up to 8.5% in the plastic state) in order to ensure adequate air in the hardened concrete.

Seven mixes were examined for air void system and with the exception of SF-1, had reasonably good air void systems. A good air void system should generally have air contents greater than 3%, specific surface higher than 25 mm⁻¹ and a spacing factor lower than 0.20 mm. Mix SF-1 had a specific surface of 18.5 mm⁻¹ and a spacing factor of 0.288 mm.

6.5 Chloride Permeability

Chloride permeability of all mixes was tested using the rapid chloride permeability test. The control mix and HR-1 had moderate chloride permeability (2,000 - 4,000 coulombs) indicative of a moderate w/c ratio Portland cement concrete⁶.

As expected, all mixes containing silica fume had low to very low chloride permeabilities (all less than 1,400 coulombs). These values are similar to those obtained from low (<0.4) water/cement ratio concrete or latex modified concrete.

Most of the fly ash mixes had moderate chloride permeabilities, however, FA-3 with 20% fly ash added had a very low permeability (581 coulombs). The combination mixes had low to very low chloride permeabilities (all less than 1,400 coulombs).

7.0 Conclusions

1. Compressive strengths of greater than 30 MPa were easily reached with substantially less portland cement than the minimum currently called for.
2. Freeze thaw resistance was excellent for all mixes.
3. Salt scaling results of most mixes were above the MTO acceptable limit of 0.8 kg/m². The mass loss tended to increase with decreasing cement contents and increasing percentages of supplementary cementing materials.
4. A good air void system was or could be achieved for all mixes with the addition of air entraining at proper dosage rates.
5. High losses of air (2.5%) between the plastic and hardened concrete can occur.
6. Most mixes exhibited lower permeabilities than the control especially those with increasing percentages of supplementary cementing materials.

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